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INFLUENCE OF ALPHA/BETA INTERFACE PHASE ON FRACTURE TOUGHNESS A--ETC(U)
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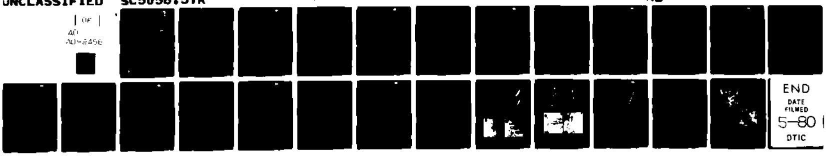

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The α/β interface phase is a microstructural feature which occurs in two-phase, $\alpha+\beta$, titanium alloys under certain processing conditions. Interface phase can grow to widths of up to ~500 nm and has been shown to exert an influence on tensile properties. In this work, its influence on fracture toughness and fatigue crack growth rate in Ti-6Al-4V has been examined.

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Compact tension specimens used for fatigue crack growth rate measurements were given sub-transus heat treatments to produce a variation of interface phase widths of from 40 to 370 nm. It was found that the sample having the broadest interface phase exhibited the greatest resistance to fatigue crack growth and that the growth rate was less than that generally observed for Ti-6Al-4V in the R.A. condition. The mechanism by which the presence of a broad interface phase improves the fatigue crack propagation resistance is the formation of numerous secondary cracks.

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INFLUENCE OF α/β INTERFACE PHASE ON FRACTURE TOUGHNESS AND FATIGUE CRACK GROWTH RATE IN TI-6Al-4V

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ABSTRACT

The α/β interface phase is a microstructural feature which occurs in two-phase, $\alpha+\beta$, titanium alloys under certain processing conditions. Interface phase can grow to widths of up to ~500 nm and has been shown to exert an influence on tensile properties. In this work, its influence on fracture toughness and fatigue crack growth rate in Ti-6Al-4V has been examined.

Fracture toughness was measured using notched Charpy bars which were heat treated below the beta transus to produce equiaxed primary alpha grains and interface phase widths varying from 60 to 500 nm. There was found to be no significant influence of interface phase width, or volume fraction of primary alpha, on fracture toughness. However, there was a significant effect of microstructure on toughness due to the presence of bands of alpha grains having a common crystallographic orientation and little or no beta phase between them. The crack propagated by hole growth along these bands with growth apparently uninterrupted by the presence of a

grain boundary devoid of beta phase. When these bands were parallel to the crack growth direction, a low toughness (77 $MN/m^{3/2}$) was observed and when they were perpendicular to the crack growth direction, a higher toughness (118 $MN/m^{3/2}$) resulted.

Compact tension specimens used for fatigue crack growth rate measurements were given sub-transus heat treatments to produce a variation of interface phase widths of from 40 to 370 nm. It was found that the sample having the broadest interface phase exhibited the greatest resistance to fatigue crack growth and that the growth rate was less than that generally observed for Ti-6Al-4V in the R.A. condition. The mechanism by which the presence of a broad interface phase improves the fatigue crack propagation resistance is the formation of numerous secondary cracks.

INTRODUCTION

The α/β interface phase is a microstructural feature which occurs in two-phase, $\alpha+\beta$, titanium alloys under certain processing conditions [1-5]. Interface phase forms as a transition phase in the $\beta \rightarrow \alpha$ transformation during slow cooling, its thickness being dependent on the cooling rate [4]. In α/β titanium alloys, cooling rate also affects the volume fraction of primary alpha, thereby complicating a study of the influence of interface phase on mechanical properties when these properties are also influenced by the volume fraction of primary alpha phase.

Interface phase, which can grow to widths of up to ~500 nm, has been shown to exert an influence on tensile properties in Ti-6Al-4V [5]. In that work, the evidence indicated that, in general, tensile yield strength increases and elongation decreases as the interface phase width increases [5]. The correlation of interface phase width and volume fraction primary alpha with tensile properties implies that other mechanical properties may also be affected by these microstructural features. This paper reports the results of a study of the influence of interface phase and volume fraction primary alpha on fracture toughness and fatigue crack propagation in Ti-6Al-4V.

EXPERIMENTAL PROCEDURE

Chemical analysis of the alloy used in this study is given in Table 1. The as-received microstructure consisted of ~90% equiaxed primary alpha particles, having ~10 μm diameter, in a continuous beta matrix.

Table 1

Composition of Ti-6Al-4V, by weight

Ti	Al	V	Fe	C	O	H	N
Bal	6.15	4.09	0.18	0.011	0.129	0.0067	0.019

Fracture toughness was measured by notched, pre-cracked Charpy bars tested in slow bend. The slow bend tests produced a value for W/A which was converted to K_Q through the expression $K_Q = [(W/A)(E/2(1 - \nu^2)]^{1/2}$. Compact tension specimens were used for fatigue crack growth rate measurements, which were carried out in laboratory air at room temperature at 10Hz and R = 0.1. Crack length was measured optically with the specimens removed from the testing machine.

Thin foils for transmission electron microscopy were prepared by conventional electropolishing techniques [6] or by ion milling [7]. Interface phase widths and volume fractions of primary alpha were measured as described previously [5].

RESULTS

1. Microstructural Considerations

The objective of this work was to examine the influence of interface phase width on toughness and fatigue crack propagation (FCP) rate. In order to do this, samples should be processed so that only the interface phase width is varied while other microstructural features which can influence properties are held constant. Among these features having an effect on properties is volume fraction of primary alpha phase. Since the interface phase only grows during slow cooling [2], treatments that vary the interface phase width may also alter the volume fraction of primary alpha, hence this microstructural feature is not easily controlled.

Another feature that can affect properties is ordering in the primary alpha grains. The slow cooling treatments used for producing various interface phase widths are conducive to ordering in this alloy. Indeed, in two of the ten fracture toughness test specimens, superlattice reflections were observed in the selected area electron diffraction (SAD) patterns of the primary alpha grains, indicating the presence of Ti_3Al (α_2) particles. In three additional fracture toughness specimens, faint superlattice reflections were observed, indicating few α_2 particles in the primary alpha. For the remainder of the toughness test specimens and the FCP test specimens, no superlattice reflections were observed. However, the absence of superlattice reflections does not preclude the existence of some degree of order of the alpha phase; indeed, some order would be expected in

an alloy with 6% Al given slow cooling treatments from high in the α/β phase field.

A third microstructural feature that can influence mechanical properties is decomposition of the beta phase. For the results presented in this paper, there have been various degrees of β-phase decomposition and, although the results would indicate that the amounts of decomposition have not significantly influenced properties, the degree of decomposition will be pointed out for each of the test specimens.

The remarks in this section indicate that microstructural features other than interface phase width have not been held constant in all test specimens. Nevertheless, it will be seen that the test results can be analyzed in terms of individual microstructural features and, although care must be taken in drawing detailed conclusions, some generalizations can be gleaned from the results.

2. Fracture Toughness

Charpy bars were notched so that the crack propagated in the plane normal to the rolling direction, advancing in the S direction in one-half the tests and in the T direction in the other half of the tests. The bars were heat treated to produce a variation in interface phase width, which also produced a variation in volume fraction primary alpha. Examination of the microstructure after heat treatment revealed a banded appearance of the primary alpha parallel to the rolling plane, as shown in Fig. 1.

Examination of these banded regions by polarized light indicates that they are composed of alpha particles with similar crystallographic orientation, different from the regions surrounding the bands. Texture analysis of the plate reveals [0001] poles concentrated in the rolling direction and in the transverse direction, and [1010] poles concentrated approximately 45° to the T and S directions. It is not clear whether the texture effects can be related to the banded regions or to the surrounding regions; nevertheless, the results indicate a concentration of basal planes parallel to the crack plane and an additional concentration of c-directions either parallel or perpendicular to the crack direction. It can be seen in Fig. 1 that a crack propagating in the S direction moves perpendicular to the bands of primary alpha and a crack moving in the T direction moves parallel to the bands. The former condition will be called a perpendicular crack and the latter condition will be called a parallel crack in subsequent discussion.

The test results of the α/β processed 6-4 are presented in Table 2.

Table 2

Charpy Bar Slow Bend Test Results for α/β processed Ti-6Al-4V

Test #	Crack Orientation	K_Q $(MN/m^{3/2})$	Volume Fraction Primary Alpha	Interface Phase Width (nm)	Superlattice Reflections in α	Beta Phase Decomposition
1	Perpendicular	154	0.85	330	Yes	None
2	Perpendicular	143	0.84	293	Yes	None
3	Perpendicular	118	0.83	376	No	Considerable
4	Perpendicular	113	0.82	223	No	None
5	Perpendicular	105	0.84	524	Faint	None
6	Parallel	80	0.78	92	No	Slight
7	Parallel	79	0.83	505	No	Considerable
8	Parallel	77	0.86	383	Faint	None
9	Parallel	76	0.68	64	No	Slight
10	Parallel	74	0.81	179	Faint	None

The fracture toughness is considerably greater for a perpendicular crack orientation than for the parallel crack orientation. Fractography of the various samples revealed that the fracture topography was strongly influenced by the underlying banded microstructure, Fig. 2.

Examination of Table 2 reveals that, for a parallel crack orientation (tests 6-10), there is no influence of either interface phase width or volume fraction primary alpha on K_Q. It can also be seen that there is no influence of the higher degree of order in test samples numbers 8 and 10, and no influence of beta phase decomposition on K_Q in these

samples. For the perpendicular crack orientation (tests 1-5) the two tests having the greatest toughness values also exhibited strong superlattice reflections, indicating the high degree of order in these samples may have some influence on toughness. The volume fractions of primary alpha, which do not vary significantly, and the interface phase widths, which vary from 223 to 524 nm, do not correlate with K_Q. There is no effect of β-phase decomposition on toughness, as can be seen by comparing test samples #3 and 4.

Although neither interface phase width nor volume fraction primary alpha influences K_Q, there is a significant effect of microstructure as manifested by sample orientation. The presence of the bands of alpha grains has clearly influenced the crack extension. Closer inspection of the bands of alpha grains reveals that several grains frequently contact without the presence of β-phase between them, Fig. 3. When this occurs, the crack propagates by void coalescence (hole growth) along these several grains, with the growth uninterrupted when it encounters a grain boundary devoid of β-phase. This results in large elongated voids in the fracture face, as shown in Fig. 4. The wavy lines within the large voids are serpentine glide resulting from the intersection of slip with the void surface; they are seen to be related to the crystallographic orientation of the underlying α particle and not a function of crack direction. The serpentine glide within the large voids is indicative of deformation prior to the void's joining the crack and opening up.

3. Fatigue Crack Growth Rate

Because this portion of the research was essentially a prefatory examination of the influence of interface phase width on FCP rates in the equiax primary alpha microstructures, only three samples were tested. These samples were heat treated so that the interface phase widths varied considerably and, as expected, the volume fraction of primary alpha phase also varied. These parameters are listed in Table 3. For these results, then, it will be difficult to separate out the influence of interface phase on FCP, since volume fraction primary alpha also varies significantly.

Table 3

Microstructural Parameters of Fatigue Specimens

Test #	Volume Fraction Primary α	Interface Phase Width, nm	Superlattice Reflections	Beta Phase Decomposition
1	0.71	64	No	Considerable
2	0.82	207	No	Slight
3	0.92	414	No	None

The results of the tests, which were run at 20°C in dry laboratory air, are presented in Fig. 5. It can be seen that at the low ΔK region ($\Delta K \approx 10 MPam^{1/2}$) there is little difference in FCP rate among the three conditions. However, at about $\Delta K = 15 MPam^{1/2}$ the curves begin to separate, with test sample #3 exhibiting better FCP resistance than samples #1 and

#2. As the stress level increases, the separation between #3 and the other two samples becomes increasingly larger, reaching a difference of an order of magnitude at the higher stress levels. Figure 6 presents plots of FCP rates as a function of interface phase width (and volume fraction primary alpha) for several stress levels. At low stress levels, there is little influence of these microstructural features on FCP rate, but as the stress level increases, there is generally an increasing dependence of da/dN on interface phase width and/or volume fraction primary alpha.

Fractography reveals that, at the low stress levels, fracture is predominantly by cleavage through the alpha phase in all three test specimens. Striations are not detected until the FCP rate reaches about 2.5×10^{-4} mm/cycle; for samples #1 and #2, this is at a stress level of about $20MPam^{1/2}$, while for sample #3, the rate occurs at a stress level of about $30MPam^{1/2}$, Fig. 7. The change in mode appears to be gradual, with the transition region showing cleavage of some α particles and striations in other α particles, Fig. 7b. There is extensive secondary cracking over the entire range of stress levels in sample #3. The secondary cracks extend both across alpha grains and along alpha-beta interfaces. As the stress level is increased, the occurrence of interface cracking increases, becoming predominant at the higher stress levels. Fig. 7d. Samples #1 and #2 exhibit little secondary cracking.

DISCUSSION

1. Fracture Toughness

Any influence that volume fraction primary alpha or interface phase might have on fracture toughness appears to have been overshadowed by the presence of the bands of primary α phase. The fracture surface is characterized by large elongated voids which correlate with the presence of several alpha grains of a similar orientation having no beta phase separating them. When these bands of alpha grains are parallel to the crack propagation direction, lower toughness values are observed because the crack advances as the elongated voids open up. This mechanism operates whether there is 68% or 86% primary alpha and whether the interface phase is 60 nm or 500 nm. Similarly, when the bands of alpha grains are perpendicular to the crack propagation direction, higher toughness values are observed because the crack moves normal to its propagation direction as it encounters elongated holes opening up. This delaying mechanism operates regardless of volume fraction primary alpha or interface phase width.

The moderate texture of [0001] poles of eight times random in the T (transverse) direction is fairly typical of rolled plate, but the eight times random [0001] poles parallel to the rolling direction is somewhat unusual. It is possible that the banded structure is associated with this latter texture. The decrease or absence of beta phase in these banded regions would also suggest microsegregation of vanadium, although no evidence

for this was obtained. At any rate, the presence of the banded microstructure leads to directionality in fracture toughness of Ti-64.

2. Fatigue Crack Growth Rate

The fatigue results indicate that microstructure influences crack growth rates, especially at higher stress levels. The fracture mode is essentially the same among the fatigue samples: cleavage-like fracture through the primary alpha particles at low ΔK (<15MPam$^{1/2}$), gradually changing to striation formation as the stress level is increased. The mechanism by which the sample having the broadest interface phase (and the highest volume fraction of primary alpha) improves the FCP phase resistance is the formation of numerous secondary cracks.

The influence of microstructure on FCP, then, is to promote additional cracking to absorb applied energy rather than impart resistance, per se, to an advancing crack. From the limited data obtained here, it is not clear whether the interface phase or volume fraction primary alpha dominates the effect. The most likely way in which increased volume fraction of primary alpha could improve crack resistance would be through an increase in the strength of the beta phase rather than any effects of larger alpha particle size or increased alpha grain boundary surface area. Increasing the volume fraction of primary alpha from 0.71 to 0.92 increases the particle size from about 9 to 10 μm and the particle surface area by about 20%. Such minor changes in these parameters would not seem likely to cause such significant effects as are observed. On the other hand, the beta phase will

be markedly enriched in vanadium as the volume fraction of primary alpha phase increases, and the solid solution strengthening thus afforded could provide increased crack resistance, forcing the crack to branch along interfaces.

Alternatively, interface phase could promote crack branching by nucleating cracks within the plastic zone ahead of the advancing crack front. If a broad interface phase inhibits the transfer of slip between the alpha and beta phases, stress concentrations would arise at the interface and cracks could form at more than one boundary within the plastic zone. As these link up to the main crack, energy is absorbed and crack branching results. Further work is needed to determine which, if either, of the mechanisms speculated on here is operative.

SUMMARY

Neither interface phase width nor volume fraction primary alpha influenced fracture toughness of α/β processed Ti-6Al-4V having a banded microstructure. Rather, the presence of bands of alpha grains significantly affected toughness by influencing crack extension. The crack propagated by void growth along these bands, resulting in low toughness when the bands were parallel to the crack growth direction and higher toughness when they were perpendicular to the crack growth direction.

The greatest resistance to fatigue crack growth was observed in material having a broad interface phase. The mechanism by which the presence of a broad interface phase improves fatigue crack propagation resistance is the formation of numerous secondary cracks.

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LIST OF FIGURES

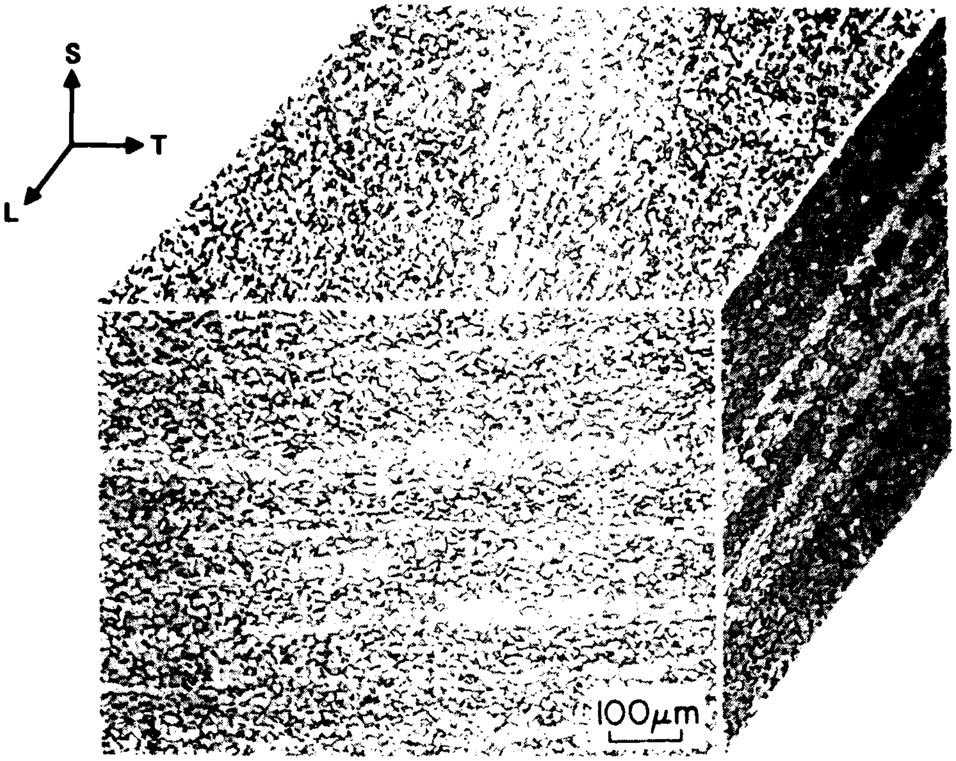

Fig. 1 Isometric view of Ti-6Al-4V used in this study. Note banding of primary alpha particles parallel to rolling plane.

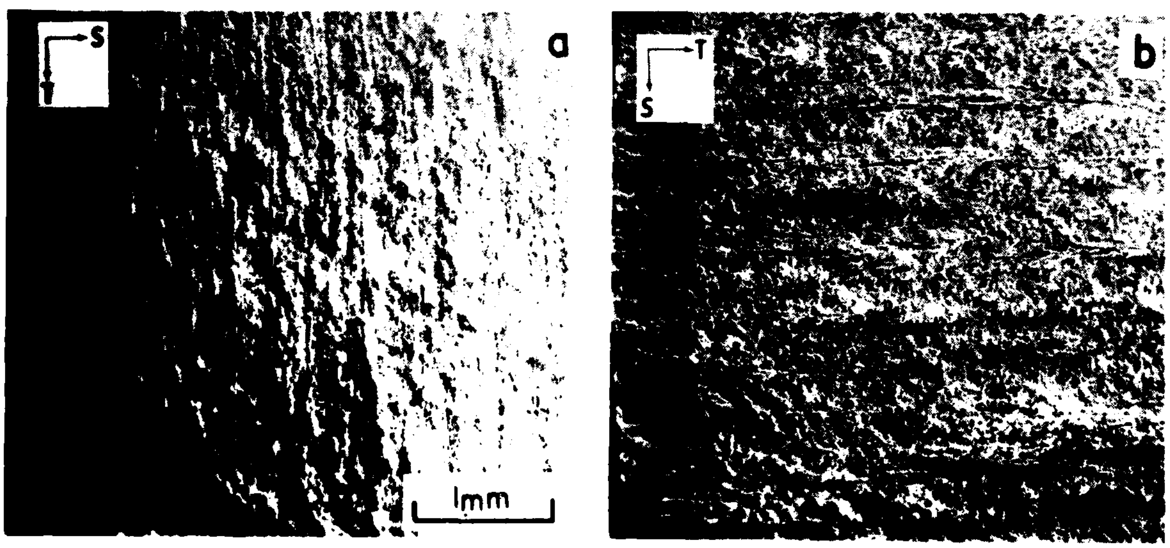

Fig. 2 Scanning electron micrographs of fracture surfaces of Charpy bars. (a) perpendicular crack moving S direction; (b) parallel crack moving in T direction. Crack direction is from left to right in both micrographs.

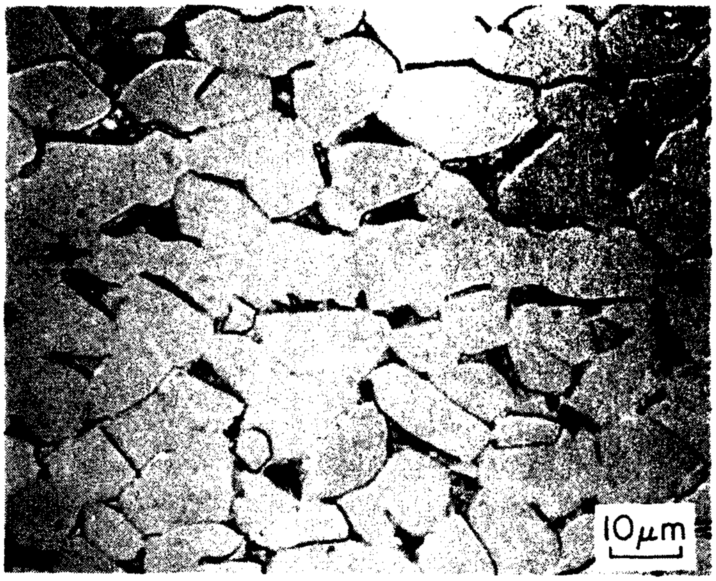

Fig. 3 Light micrograph of Ti-6Al-4V showing a band of several contiguous alpha grains (between arrows).

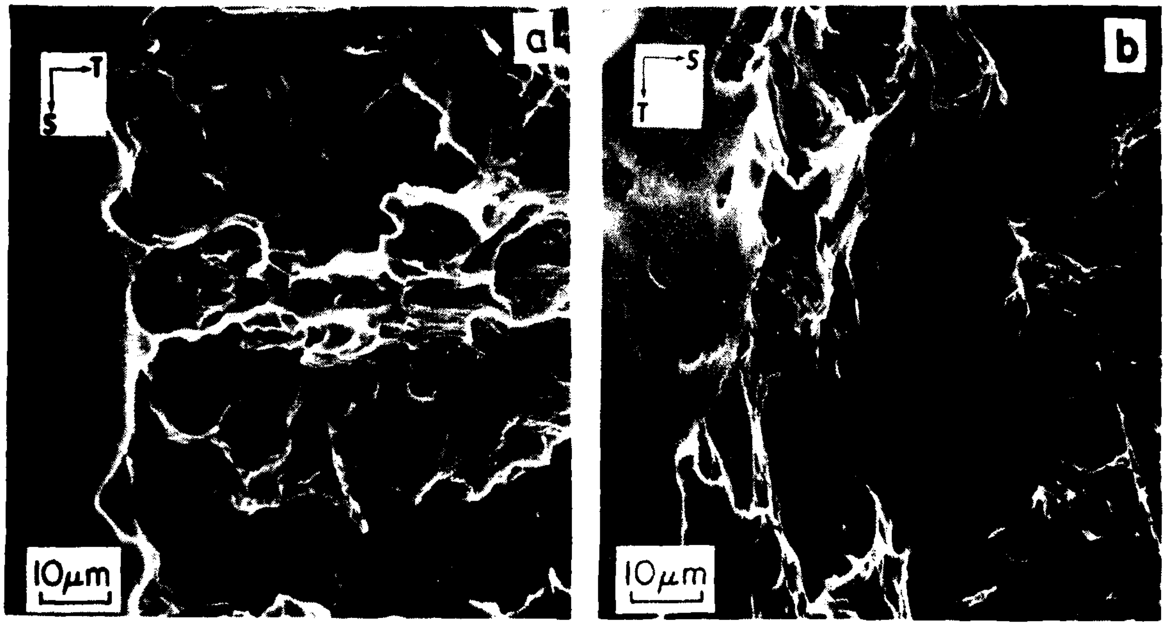

Fig. 4 Scanning electron micrographs of fracture surfaces of Charpy bars. (a) parallel crack moving in T direction; (b) perpendicular crack moving in S direction. Crack direction is from left to right in both micrographs. A portion of the fracture surface has been etched to reveal underlying microstructure in each micrograph.

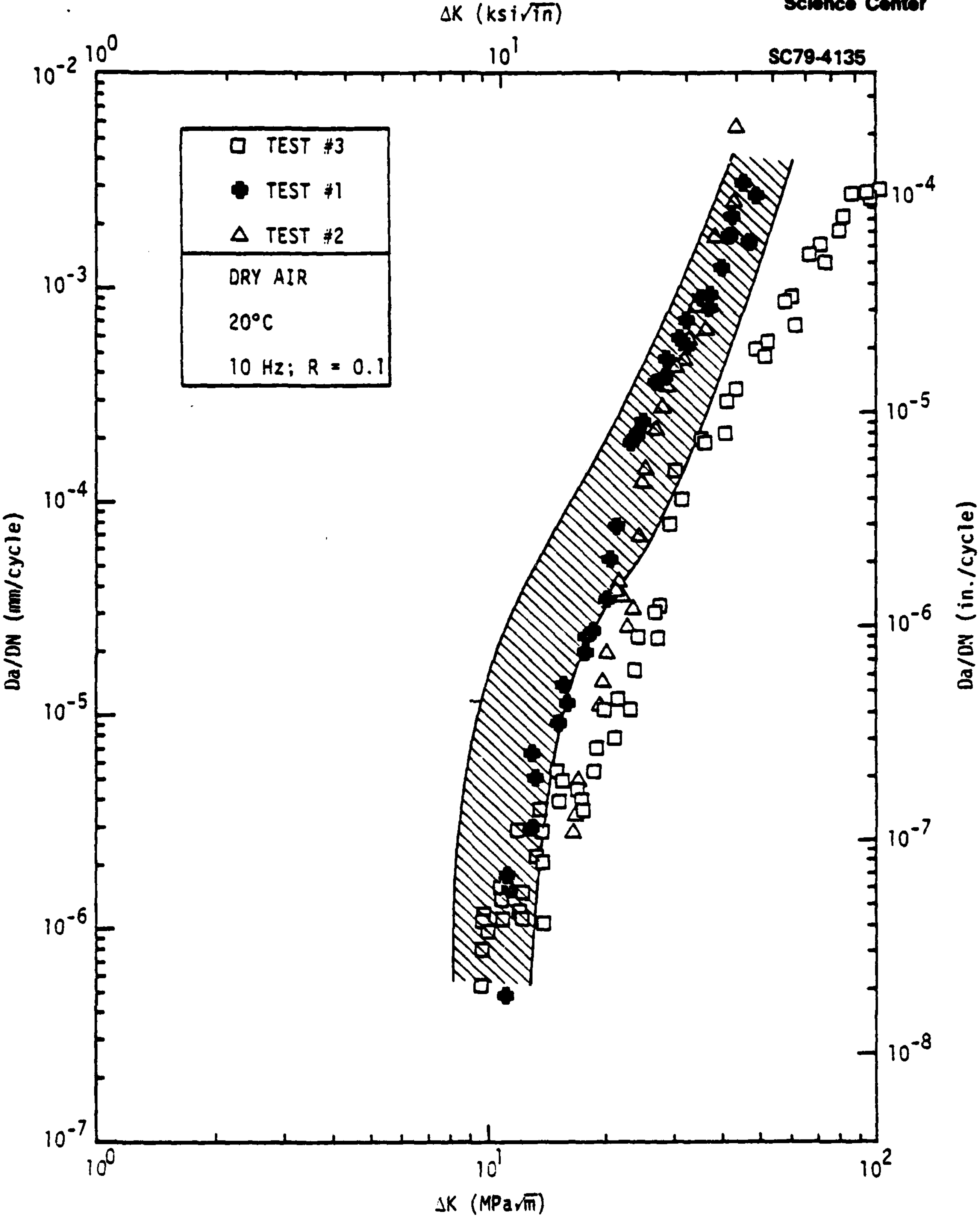

Fig. 5 Fatigue crack propagation rate as a function of applied stress for three microstructural conditions of Ti-6Al-4V. The band is a typical scatter band for Ti-6Al-4V in R.A. condition.

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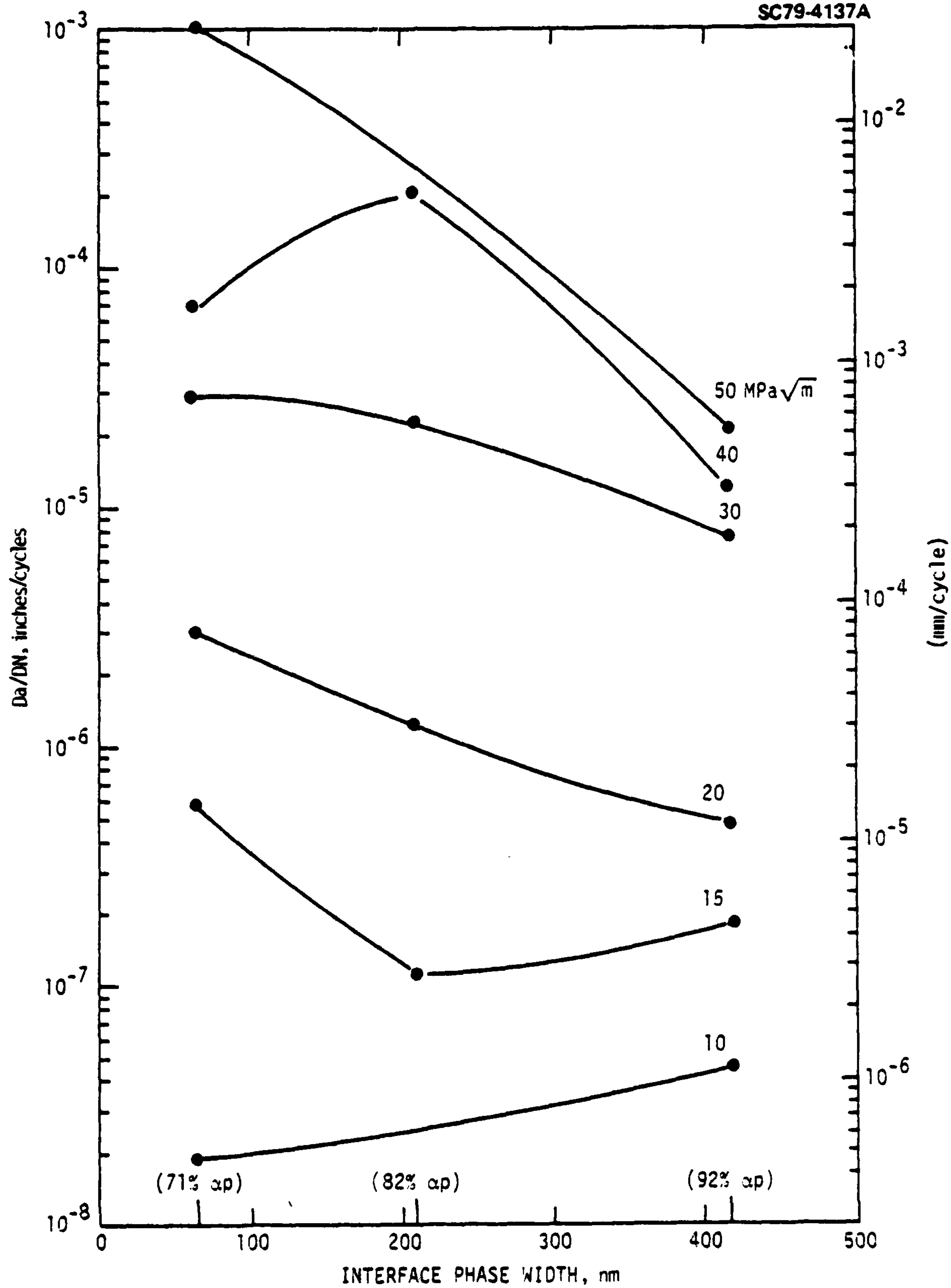

Fig. 6 Fatigue crack propagation rate as a function of interface phase width (and volume fraction primary alpha) for several stress levels.

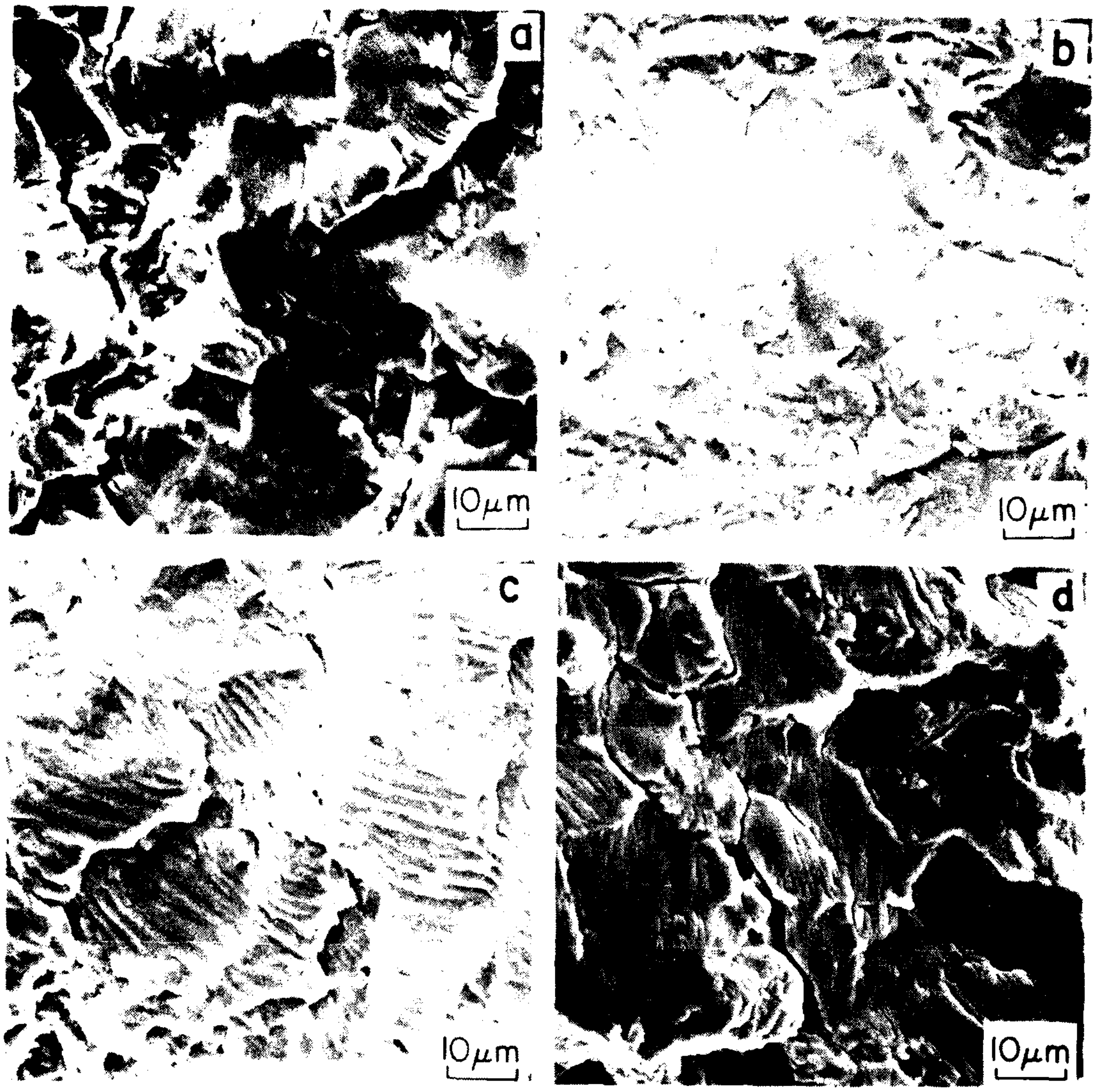

Fig. 7 Scanning electron micrographs of fracture surfaces of FCP Ti-6Al-4V samples. (a) test specimen #2, ΔK = 30 MPa $m^{\frac{1}{2}}$; (b) test specimen #3, ΔK = 30 MPa $m^{\frac{1}{2}}$; (c) test specimen #2, ΔK = 40 MPa $m^{\frac{1}{2}}$; (d) test specimen #3, ΔK = 40 MPa $m^{\frac{1}{2}}$.